Technical Report Sheet

Multi-objective Optimization of Window-to-Wall Ratio Considering Energy and Daylighting: A Case Study in an Existing School Building in Cebu, Philippines

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Overview:

This research project aims to study the Window-to-Wall Ratio (WWR) for every orientation that corresponds to the four cardinal direction (North, South, West, and East) in a school building in Cebu, Philippines that could lessen its cooling and lighting energy consumption with the adequate exploitation of daylight inside the building space.

The objectives of this research work are:

Objectives

[1] To establish a building energy model of the SAFAD building using EnergyPlus software and calibrate the energy and illuminance output of the simulation using measured data from the building.
[2] To determine the WWR range for every orientation that will cause the least cooling and lighting energy consumption for the building through parametric analysis.
[3] To determine the WWR range that will pass the daylighting criteria using Useful Daylight Illuminance (UDI) metric.

Keywords: Window-to-Wall Ratio (WWR); Daylighting; Window Retrofit; Building Energy Efficiency; EnergyPlus; Building Energy Simulation

1. Theoretical Background

Buildings have significant impact to the society and to the environment. They are responsible for 36% of the world's total energy consumption and for 40% of the world's total greenhouse gas emission [1]. In the Philippines, buildings account for 36% of national energy consumption [2]. The increasing population of buildings puts a burden on the country's supply for energy because of the direct relationship between buildings and the country's energy demand. Since the Philippines is still heavily dependent to non-renewable energy sources [2], the country's pursuit for industrialization will really be tied up with its economic and environmental concerns.

Energy efficiency in buildings (EEB) is a vital step to lighten the environmental and economic burden due to buildings [3]. The concept of EEB is to use lesser energy for building operations (e.g. heating, cooling, lighting, etc.), without compromising the health or comfort of its occupants as well as the functionality of the building. EEB could be classified into many forms: building energy management (building commissioning, energy monitoring, energy benchmarking and standardization, energy labelling, etc.), behavioural (e.g. giving the occupants direct control of the building systems to alter the energy consumption), and technical (improving the system of the building) [4]. The technical aspect of EEB could be in the form of improving the mechanical systems (e.g. heating, ventilation, and air conditioning systems), improving lighting systems, assessing building performance for retrofitting, micro-generation using renewable energy sources, and finally enhancing the building's envelope (walls, windows, roofs, etc.).

Among building envelopes, windows are found to be the most crucial feature of a building in permitting the gain and loss of energy [5] making them capable of not only providing daylight [6] but also influencing the building's total energy consumption [7] [8] [9]. The heat gain and heat loss through windows can be associated into these three following parameters: window size, window orientation, and window's thermal properties [10].

However, window size is found to be one of the most influential window parameter to the energy consumption [11] and daylight provision [11] [6] in buildings. That is why it became a subject for many optimization studies. But when optimizing window size in an extremely hot and humid country like the Philippines, a dilemma rises because major part of the country's energy demand comes from cooling and lighting, two energy consumptions that have contradicting characteristics. When trying to maximize daylight to save lighting energy demand, intuitively, larger windows need to be applied. However, when trying to lessen cooling energy consumption, there is a need to inhibit the penetration of solar radiation to the building space which in turn requires smaller windows. What makes it even more complicated is the visual comfort of the occupants. The Philippines is located in the Asian tropics where there is an abundant supply of daylight, allowing too much penetration of daylight may cause over glare to the building occupants, while inhibiting too much daylight may go against the occupant's preference. Thus, these contradicting scenarios in deciding the optimum window size in an extremely hot and humid climate like the Philippines need multi-objective optimization process that simultaneously evaluates energy consumption and daylighting [12] [6].

Furthermore, Philippines is a developing country which has a significantly low rating in terms of EEB related policies [13]. There are no significant guidelines that are strictly observed in the designing process of new buildings and for retrofitting buildings to enhance their energy performance. The country is still in the phase of institutionalizing rules for energy efficiency and conservation [14]. But there are no existing studies that focus on the enhancement of building envelope which are specified for applicability in the Philippines that could be used in the design phase and retrofitting of energy efficient buildings, and also to support strict guidelines related to EEB in the future.

The present work aims to study the window to wall ratio (WWR) for every orientation that corresponds to the four cardinal direction (North, South, West, and East) in a school building in the Philippines that could lessen its cooling and lighting energy demand with the adequate exploitation of daylight inside the building space.

1.1 Window Optimization

Windows are found to be major contributors in the loss of energy in the building space. In Norway, it was reported that 40% of the heat loss in a typical office building are due to windows, outranking the contribution from other parts of the building envelope specifically walls, air leakages, thermal bridges, floor, and roof [5]. The heat flow through the window is basically characterized by its thermal properties – U-value (thermal transmittance), g-value (total solar energy transmittance), and air leakage [15]. Moreover, the heat gain and heat loss through windows can be associated into these three following parameters: window size, window orientation, and window thermal properties [10]. Furthermore, aside from heat, glazed windows are also major contributors in the penetration of daylight in the building space [16]. Because of these, there have been many research works that optimizes windows to enhance the energy performance of buildings [17].

1.1.1 Window Size Optimization: Energy Consumption

Window size is said to be the most influential window parameter to the energy consumption and day-lighting in a building. A sensitivity analysis [16] reveals that among studied parameters, namely window to floor ratio, shading transmittance, shading front and back reflectance, space aspect ratio, insulation thermal resistance, and glazing type, window to floor ratio has the most impact to annual daylighting, annual heating demand, and annual cooling demand. It was also found out [6] that among WWR, wall reflectance, and window orientation, WWR has the highest influence on lighting energy demand and to four day-lighting assessment metrics. The high influence of window size to the cooling energy demand, heating energy demand, and day-lighting made it a subject for many optimization studies to save energy consumption.

The first found record of window size optimization study in the viewpoint of energy consumption is from Francisco Arumi [18]. He studied the effect of WWR on the heating, cooling, and lighting energy demand in Austin, Texas and concluded to an optimum range of window area from 10-40% that can potentially save energy up to 50% relative to a "windowless" configuration. Later on, a study from Johnson et al. [19] has been recorded, again optimizing to get the least total energy consumption but this time window orientation and the window's glazing properties are included in the studied parameters. Then years later, along with window size, building's geometric details have been included in recorded optimization studies, specifically the building's aspect ratio [20] and the room size [21]. The former considers heating and cooling energy demand while the latter considers total energy consumption as the metric for optimization and were studied for residential and office buildings respectively. Then another research work which studied the same parameters as [21] is from Ghisi and Tinker [22] only they differ in the metric used for optimization, in which this time it is more focused on the lighting energy consumption. Specifically, it was about the integration of daylight into the building space to lessen lighting energy demand. Later on, consideration of shading devices [7] in the study of window size has been recorded. Along with wall thermal properties [23], building insulation, thermal mass, different glazing systems, and even colour of wall [24] [25] [26] were studied to maximize further energy savings. Then the inclusion of other building features such as curtain walls can also be found [27] in the literature. More recent related studies can still be found [28] [29] [9] [8] [30] [31]. The parameters being studied are not so different to the earlier studies aside from one [9] where they included in the parameters being studied the window position. In the case of two other studies [8] [31], they used different approaches in the optimization process which is through optimization algorithms aside from the common graphical analysis. The former used *harmony search algorithm* which is an algorithm inspired from the musical process of searching for the perfect harmony and the latter used *genetic algorithm* which is an evolutionary algorithm that is inspired by the natural selection.

Giving the exact value of the optimum window size to summarize the results of the aforementioned studies is however not possible because optimum window size is a case to case basis, as observed in the mentioned studies, optimum window size depends on various factors. It could be climate, building type, glazing properties, or simply the priority of the optimization process. However for simple understanding, in terms of lighting along with heating energy demand, larger window size is more favourable [32] [26] while for the purpose of lesser cooling energy demand, a smaller window size is more favourable [32].

1.1.2 Window Size Optimization: Energy and Day-lighting Assessment

It is found that integration and effective use of daylight in buildings is key in achieving energy savings [22]. But it is important in optimizing windows that aside from minimizing the energy consumption, there should be an assessment of day-lighting in the building space [33] to consider the visual comfort of the building occupants. Thus, multi-objective optimization of window size with simultaneous evaluation of energy performance and day-lighting is important. However, compared to studies that focuses solely on energy there are only few studies that conduct simultaneous evaluation of energy performance and daylight assessment.

A study from Ochoa et al. [33] optimizes window size with simultaneous evaluation of total energy consumption and day-lighting. In that study, to assess the daylighting performance there should be at least 50% of the total occupancy hours that illuminance of 500lux is observed in the office space. For the visual comfort side of daylighting assessment, two criteria were used. Uniformity Ratio (UR) and Daylight Glare Index (DGI). UR between two reference points of not more than 3.5 and DGI of not more than 22 both for a minimum of 50% of the total annual occupancy hours. The window size that will give the least total energy consumption at the same time passes the day-lighting performance and passes one of the two criteria for visual comfort will be deemed as optimum. A similar study [34] was also conducted. This time, solar shading set-point and window size for an energy efficient office building in Frankfurt, Germany was being considered. The day-lighting performance and visual comfort was assessed through Daylight Autonomy (DA) with 500lux being the threshold and Useful Daylight Illuminance (UDI) respectively. DA500 is the percentage of the total annual occupancy hours that had the illuminance of at least 500 lux being met inside the office space [35]. UDI however measures the frequency of daylight in the building space within a specific range (100-500lux, 500-2000lux, >2000lux), 100-500 lux being the range for considered effective with daylight alone or the supplementation of artificial lighting, 500-2000 lux is either desirable or at least tolerable, and >2000 lux is said to cause visual and/or thermal discomfort [36]. The range of window size that will give the least total energy consumption and at the same time passes the defined criteria for day-lighting assessment will be concluded as the optimum range. They also added a robustness test to investigate how variable is the optimum range of window size when subjected to change in building geometry (surface area to volume ratio) and Heating, Ventilation, and Air Conditioning (HVAC) efficiency. This study was replicated with minimal changes by Goia [12]. This time, it considers four different European climate (Oslo, Frankfurt, Athens, and Rome) and added a robustness test through changing the efficiency of artificial lighting. The workflow of this study is basically the same from the previous one. A research conducted by Lartigue et al. studied the effect of window to wall area ratio (WWR) and the window type characterized by its visual and thermal characteristics (visual and solar transmittance, and U-value) to the heating load, cooling load and day-lighting performance [37]. Day-lighting performance is quantified using Annual Deficient Daylight Time (ADDT) and a threshold of 300 lux is set for the ADDT metric. The goal was to minimize the ADDT300 since this will mean that there is a minimal duration of illuminance lower than the 300 lux threshold in a year. Another research studied the effect of WWR, wall reflectance, and window orientation to the various day-lighting metrics (Average Daylight Factor, Average Uniformity, Daylight Autonomy, Useful daylight Illuminance, and simplified Daylight Glare Probability) and annual lighting energy demand of an office building in Indonesia [6]. He performed a sensitivity analysis through multiple linear regression to know which among the studied parameters greatly influenced the considered output. Multi objective optimization using Pareto analysis was performed to arrive to the optimum parameters. There was an investigation on the effect of building aspect ratio, building orientation, depth of overhang for south facade, WWR for each facade, window position for each facade, and window visible transmittance to the Annual Glaring Index (AGI) and Annual Energy Requirement (AER) in an existing office in Canada [11]. A very recent study that optimizes WWR in an existing hotel building with solar shading situated in China's climate condition can also be found [38]. There was a simultaneous consideration of visual performance through Daylight Factor and cooling energy demand. First objective of the study was to find the minimum WWR that will meet

China's day-lighting requirement. Then computer simulation was applied using the found WWR to calculate the baseline cooling load. The cooling load was again calculated through heat balance equation with various WWR values and solar shading scenarios. A range of WWR values that deliver lesser cooling load with respect to the baseline cooling load was then proposed. Finally, the range of WWR that were proposed previously were tested to verify if they passed the day-lighting requirement. During this stage, the final optimum WWR was then proposed.

1.1.3 Climate and Window Size Optimization

Climate is a vital factor in concluding to the optimum window size [4]. A study [20] wherein south window size, building aspect ratio, and insulation thickness of the building were investigated for five different locations in Turkey. It shows that the optimum value of south window size that could reduce cooling and/or heating load is 90 and 25% WWR for those locations that are experiencing cold (Erzurum, Ankara) and hot climate (Diyarbarkir, Izmir, Antalya) respectively. Added to that is a study [21] about getting the window size for different orientations and building size that will give the least energy consumption. It is located in seven different cities in Brazil and one city in the United Kingdom. It is difficult to summarize all the results of the optimum window sizes because of the many parameters considered, but for easier comparison, considering only the width to depth ratio of room of 1:2, room index of 5, and orientation of north, the optimum window sizes are: 87% WWR for Leeds in UK, and 49, 62, 64, 51, 51, 40, 32% WWR for Belém, Brasília, Curitiba, Florianópolis, Natal, Rio de Janeiro, and Salvador, respectively. Another study [32] showed five different climate zones in Asia (Manila, Taipei, Shanghai, Seoul, and Sapporo) for an office building typology wherein they arrived to a varying optimum values of WWR for each climate zones studied. Another study [12] investigated the WWR for four different climate zones in Europe. However, because the building being studied is an energy efficient building, values of optimum WWR is usually in between 30-45% WWR. But considering south facing facades, it has the most varying optimum value of WWR which can be as high as 60% for cold climates and as small as 20% WWR for warmer climate.

1.1.3.1 Climate and Daylighting in Cebu, Philippines

Cebu, Philippines is located in the Asian tropics around 10° latitude and 123° longitude. It has around 12 daylighting in between sunrise and sunset on average. The lowest daylighting hours is normally on December of around 11.5 hours and highest on June which is almost 13 hours [39] (see Figure 1.1).

Climate in the Philippines is classified by ASHRAE into three different climate zones (0A, 1A, and 2A) [40] (see Table 1.1). Most of the municipalities and cities belong to climate zone 0A which is classified as extremely hot regions and only one city in the Philippines belongs to the hot region. The letter A after the thermal zone number means that the region is humid, this is why the major part of buildings' energy consumption in the Philippines come from cooling and lighting. Thus heating and humidification is rarely used in the country.

Cebu is classified by ASHRAE as extremely hot and humid. The data is from a station placed in Mactan, Cebu, Philippines. It has greater than 6000 annual cooling degree days with base of 10°C. Cooling degree day is equal to the °C difference between the mean temperature in a given day and the base temperature 10°C – minimum outside temperature where cooling is not needed inside a building space. Heating is not needed for the entire year according to Heating degree days below 18.3°C data available from NASA [39]. Cooling is very much needed during the month of May and very less needed during the month of February (see Figure 1.2).

1.1.3.2 Studies Relevant to the Philippines and the Observed Gap

Some of the studies mentioned in the previous sections have the same climate with the Philippines which means they could possibly be applied in designing and retrofitting buildings in the country.

Ghisi and Tinker [21] studied the window area, orientation, and room size to minimize the total energy consumption in seven cities in Brazil and a city in UK. Some of the considered locations in the study are classified by ASHRAE [38] as 0A and 1A, which are also the climate classification of most cities in the Philippines. Results show that the energy consumption is lower for the room ratios whose façade is smaller and the ideal window area depends on the orientation and facade area.

Another study which is conducted in Brazil (climate zone 1A) can be found [7]. The parameters being studied are WWR, window control, window material, and interior shading. Results show that 30% WWR is ideal when considering a good trade-off of lighting and air conditioning/ventilation consumption, decreasing or increasing further results in increase in lighting or cooling consumption, respectively. There is 13.4% reduction of energy consumption from baseline with little increase savings of 13.6% when using low-e glasses and 14.4% using interior shading.

Another study [6] which has the same climate as the Philippines, was conducted in a neighbour country of the Philippines which is in Bandung, Indonesia. Bandung is classified by ASHRAE as climate zone 0A which represents most of the cities in the Philippines. They studied the effect of WWR, wall reflectance, and window orientation to various day-lighting metrics (Average Daylight Factor, Average Uniformity, Daylight Autonomy, Useful daylight Illuminance, and simplified daylight glare probability) and total lighting energy consumption. The optimum configuration of building envelope parameters in the context of the study are: WWR 30%, wall reflectance of 0.8, and south orientation. But the scope of this study only extends to lighting energy consumption and day-lighting assessment.

However, studies that optimizes window size with simultaneous evaluation of cooling, lighting, and daylighting is still lacking. Which is the focus of the present study. [21] and [7] both did not consider daylighting assessment while [6] did not include cooling energy consumption.

1.2 Philippines: Energy Efficiency in Buildings Guidelines

A study from Regulatory Indicators for Sustainable Energy (RISE) [41] shows that the Philippines lacks building energy codes to be followed during the design and retrofit of buildings to enhance their energy performance. RISE is a set of indicators that evaluates the quality of policies to support sustainable energy goals in terms of energy access, energy efficiency, and renewable energy. Philippines scored zero in all sub indicators of building energy codes (e.g. codes for new residential and commercial, are renovated buildings required to meet building energy codes, are there mandates for new building stocks to improve their energy performance, etc.).

Philippines has really no strict guidelines in terms of EEB. The country has yet to institutionalize rules and regulations for energy efficiency and conservation, the Energy Efficiency and Conservation Act of 2017 [40].

2. Significance of the Research Work

The results of this study would contribute to the advancement of existing body of knowledge since this study is conducted because of the observed gaps, namely: lack of window size optimization studies that consider simultaneously energy consumption and daylight assessment in an extremely hot and humid location, and lack of research about enhancing energy performance of buildings through the enhancement of building envelope that is designed for applications specific to the Philippines.

Since there are no guidelines yet in the Philippines, the result of this study could possibly be used in designing and retrofitting energy efficient buildings in the country. It could also influence the mindset of building designers in the country in the decision making process during the stage of designing buildings – that building features like windows do not only contribute to the aesthetics of a building but also to its energy performance and occupants' visual comfort.

The advancement of window optimization is already evident in other countries, but since results differ with varying scenarios (cimate, building characteristics, etc.), it is a must that studies conducted specifically in the Philippines grow in number to back-up future guidelines and implementing rules and regulations in designing and/or retrofitting energy efficient buildings in the Philippines.

The success of this study is a step for the design of highly energy efficient buildings with the consideration of occupants' visual comfort in the Philippines to support the bigger goal of the country relating to building energy efficiency.

3. Scope and Limitations

This work aims to study the WWR for every orientation that corresponds to the four cardinal directions (North, South, East, and West) that could deliver the least cooling and lighting energy consumption and exploit adequate amount of daylight for occupants in a school building situated in Cebu, Philippines. Therefore the parameters being investigated are only the window size in terms of window to wall ratio (WWR) and window orientation. Equally important properties of window such as solar heat gain coefficient (SHGC), U-values, and visible light transmittance (VLT) that could have significant effect to the output considered is beyond the scope of the study. Also, the output being considered in arriving to the optimum WWR are lighting and cooling energy consumption only. The day-lighting assessment is done using the UDI metric only. Lighting and cooling are the only energy consumption considered because the school building does not have heating and humidification systems, moreover, heating is very rare in the Philippines.

The building model used is an existing and occupied school building from the University of San Carlos in Cebu, Philippines. The building geometry, equipment, occupancy schedule, and equipment schedule is according to the existing data that could be extracted through on-site data gathering from the building and building activities. Because it does not represent the entirety of school buildings in the Philippines nor in all countries in the Asian tropics, the results in this study does not guarantee its applicability to all school buildings in the mentioned region; thus the results of this study are only valid to buildings with the same details.

4. Research Design and Methodology

4.1 Establishing the Baseline Model

The first part of this methodology is to establish the model of the building before the parametric analysis or the alterations of the window parameter studied (WWR). It is calibrated to be an "acceptable" representation of the building studied.

4.1.1 The Building Model and Climate Condition

The building model to be studied is the SAFAD building which is an existing and occupied building in the University of San Carlos in Cebu, Philippines. To proceed to the modelling proper in EnergyPlus, the following data are required [42]:

- Location and weather file
    - Location of the building is in Cebu, Philippines. Necessary data like longitude, latitude, time zone, and elevation are to be determined.
    - Weather file to be used is the available "typical year" weather file for Mactan, Cebu, Philippines which is provided by White Box Technologies – a recommended private source weather file provider for simulations by EnergyPlus. "Typical year" weather file is the most representative of long term record by concatenating twelve calendar months of different years, each month selected as the most "typical" in comparison to the long term record for that particular month.
- Building Construction Information
    - Details of surface constructions of the building are needed, this pertains to the materials used, what is the layering of the materials (if applicable), and what are the corresponding properties of the materials. All these for each building geometry – walls, roof, floor, and windows. See Tables 4.1 and 4.2.
- Lighting, equipment, occupants, and ACU details
    - Data regarding artificial lighting, equipment, and occupants are to be gathered per rooms of the building. Refer to Table 4.3

4.1.2 EnergyPlus

The lighting energy consumption, cooling energy consumption and internal illuminance is determined with the use of EnergyPlus software; thus the necessary inputs mentioned in the previous sections in this methodology are to be inputted to the software. The energy consumption to be utilized from the EnergyPlus simulation is the lighting and cooling energy demand for the whole building. However, for the illuminance, a single room is to be selected for simplicity of the calibration later on. Since EnergyPlus only allows two reference points, illuminance from two reference points in a single room are to be utilized. Two points are to be set as the reference points in EnergyPlus. This would also be the place of the illuminance sensors that would be used for validation later on.

EnergyPlus has been widely used for many window size optimization studies, especially in the view point of energy [16] [28] [9] and even up to the more advanced methods of optimization in the present [8] [31]. However, it is found that EnergyPlus has limitations in evaluating day-lighting. Ramos and Ghisi [43] found that EnergyPlus has limitations in the calculation of daylight factor and external illuminance values when compared to more advanced day-lighting tool like Radiance program. He compared measured data of external illuminance in Brazil to the model developed by Perez et al. [44] which is the model used by EnergyPlus for external illuminance. EnergyPlus shows overestimation in the external illuminance values. Moreover, EnergyPlus shows inaccuracy in the calculation of internal illuminance due to reflections as compared to Radiance. However, it is worth noting that in the view point of internal illuminance calculation, EnergyPlus has maximum difference of only 20% when compared to Radiance, which means that EnergyPlus can still deliver acceptable result for internal illuminance. Which is also the reason why Goia et al. [34] still used EnergyPlus for their day-lighting assessment. In their study, window size is being optimized with simultaneous evaluation of energy and day-lighting (UDI and DA). It also considers solar shading devices. This study was replicated [12] and considered four different European climate (Oslo, Frankfurt, Athens, and Rome). Both studies use EnergyPlus for building energy simulation. Another study [33] was conducted to optimize again the window size with simultaneous evaluation of total energy consumption and day-lighting by performing whole building computer simulation in EnergyPlus.

4.1.2.1 Modelling Windows in EnergyPlus

EnergyPlus [45] follows the thermal and solar/optical modelling procedure of windows from WINDOW 4 [46] and WINDOW 5 [47] programs.

4.1.2.2 Thermal Calculation

The temperatures for every face of glazing layers is solved through heat balance equation for every face [48]. There are two faces for every glazing layer and the number of equations is the number of total faces. For example, double glazed window will have four faces (refer to Figures 4.1 and 4.2) and will require four equations to solve.

4.1.2.3 Daylighting

Methods from DOE-2 [49] is used in the calculation of interior daylight illuminance from windows [48]. It is calculated by dividing the window into smaller parts and calculating the daylight that reaches the reference point coming from each parts. Luminance of the sky, angle of incidence of light on each part, and glazing visible transmittance at this angle are considered. However, EnergyPlus only supports two reference points [43]. Then the calculated daylight coming from each part of window is summed up to arrive to the total direct illuminance at the reference point. Illuminance due to reflection of light from room surfaces to the reference point is also calculated. The daylight factor is then calculated hourly by obtaining the ratio of interior to exterior horizontal illuminances. The exterior horizontal illuminance is obtained using the model from Perez et al. [44].

4.1.2.4 EnergyPlus Validation and Calibration

To use Building Energy Models (BEM) like EnergyPlus models with certain degree of confidence, it is necessary that the model closely represent the actual performance of building being modelled [50]. Achieving that, means that the discrepancies between BEM predictions and actual performance of building should be reduced through calibration process. ASHRAE [51] states a calibration procedure recommended by Kaplan [52] which is in the form of checking the input and output parameters of the model. Simulation inputs include: building orientation, zoning, external surface characteristics (orientation, area, zone assignment, thermal resistance, shading coefficient), lighting and plug load power densities, operating schedules, HVAC system characteristics (CFM, input power, zones served, minimum outside percentages, system types, heating and cooling capacities, fan schedules), plant equipment characteristics (type, capacities, rated efficiency, part-load efficiencies). On the other hand, simulation outputs include: HVAC systems satisfy heating and cooling loads, Lighting and equipment schedules are appropriate, fan schedules are appropriate, ventilation air loads are appropriate, and HVAC plant efficiencies are appropriate.

After calibrating the model, it is then validated to know if the discrepancies between the model predictions and actual measured data are acceptable. One of the most common validation technique is statistical comparison technique through two standardised statistical indices [50], Mean Bias Error (MBE) and Coefficient of Variation of the Root Mean Squared Error (CV(RMSE)). MBE measures how close the model prediction to the actual data is and CVRMSE determines how well a model fits the data; the lower CVRMSE, the better calibration performance.

1. MBE (Mean Bias Error)

$$\text{MBE} = \frac{\sum_{i=1}^{n}(m_i - s_i)}{\sum_{i=1}^{n}(m_i)}$$

Where: mi and si are the measured and simulated total energy consumption for every instance; n is the number of data points.

2. Coefficient of variation of the root mean squared

$$\text{CV RMSE} = \frac{\sqrt{\frac{\sum_{i=1}^{n}(m_i - s_i)^2}{n}}}{\bar{m}}$$

Where: mi and si are the measured and simulated total energy consumption for every instance; n is the number of data points and $\bar{m}$ is the average of the measured data points.

There are three international guidelines that set the criteria for MBE and CVRMSE (as presented in Table 4.4), namely: American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) Guidelines 14 [51], International Performance Measurements and Verification Protocol (IPMVP) [53], and M&V Guidelines for Federal Energy Management Program [54]. Criteria for the two statistical indices differ if model is validated hourly or monthly. According to Coakley et al. [50], currently, BEM are considered well calibrated if they meet the criteria set by ASHRAE [51].

4.1.2.4.1 Validation of Total Energy Consumption

Output of hourly total energy consumption for one month from EnergyPlus of the whole building will serve as the simulated total energy consumption. On the other hand, sub-metering which is capable of logging hourly total energy consumption for one whole month of the whole existing building is to be done. Output of the sub-metering will serve as the measured total energy consumption.

The simulated total energy consumption will be validated by comparing it to the measured total energy consumption. Hourly data is being utilized in the validation phase and is done through statistical comparison techniques – MBE and CV RMSE.

4.1.2.4.2 Validation of Illuminance

Since day-lighting is one of the output considered in this multi-objective optimization process, it is only appropriate to validate the model and see if it calculates the daylight entering the building space acceptably. Illuminance output from EnergyPlus which is set in the two reference points in a single room will serve as the simulated illuminance. Decoration of illuminance sensors that are capable of logging hourly illuminance data to the same reference points and to the same room that is set in EnergyPlus is to be done. The illuminance data from these sensors will serve as the measured illuminance.

For the validation of the model in the view point of illuminance, the simulated hourly illuminance is compared to the measured hourly illuminance which is replicated to the two reference points. The same statistical indices used in the calibration of energy consumption are utilized in the validation of illuminances – MBE and CV RMSE [43].

4.2 Parametric Analysis, Data Processing, and Data Analysis

After calibrating the model to be an acceptable model, the parametric analysis can now be done using the model. The parametric analysis is generally the alterations of window sizes in the form of window to wall ratio and investigate its impact to the total energy demand and assess its day-lighting performance which is replicated to all four orientations. The parametric analysis applied in this study uses the method used by Goia et al. [34]. The UDI criteria are preserved from what is used in that study. However, modifications are made to the irrelevant parts of that procedure that does not serve the purpose of the present study.

4.2.1 Simulation Set-up

Five discrete WWR values are simulated, from 10% to 90% with an increment of 20%. There are only five WWR utilized to limit the number of simulations. The five WWR values are simulated for every orientation that corresponds to the four cardinal directions (North, South, West, and East).

The simulation for energy consumption and daylight are through EnergyPlus software, simulation is made for one whole year and the output is in hourly basis. The set-point for illuminance should be set as desired. Electric lighting control is to be simulated to be able to capture what is the artificial lighting demand to supplement the daylight to achieve the desired illuminance set-point. And for simplicity, two reference points from a single room is chosen from the whole building model for the day-lighting analysis.

4.2.2 Data Processing

The aim of the study is to determine the optimum WWR value that could give the least total energy consumption where the total energy consumption is equal to the sum of lighting and cooling energy – Eq. 1. The aim function is Eq. 2

$$ET = EL + EC \qquad \text{Eq. 1}$$

$$f : \min\{ET(WWR)\} \qquad \text{Eq. 2}$$

At the same time, day-lighting analysis using the UDI metric is also made for each WWR ratio values.

4.2.2.1 Data Processing for Energy Consumption

The total annual energy consumption (Eq. 1) for various WWR values in every cardinal direction are to be presented. However, to limit the number of simulations, five WWR values are only to be utilized. This will also cause discontinuity in the function – ET(WWR). But the desired output is a continuous ET(WWR) in the range of 10-90% WWR to be able to capture the total energy consumption that corresponds to the WWR inside the 20% increment or gap. To make the discontinuous function a continuous one, spline interpolation is to be applied using MatLab.

After that, the WWR value that corresponds to the minimum ET (Eq.2) will be proposed for the next step which is the day-lighting assessment. Because close results of ET as a function of WWR is possible and also for practicality, the WWR value will be given in range. MatLab will also be utilized for this part of the procedure.

4.2.2.2 Data Processing for Day-lighting Assessment

After arriving to the WWR that gives the least energy consumption (min{ET(WWR)}). The five WWR values will undergo a day-lighting assessment. The metric used for the assessment is UDI (Useful Daylight Illuminance), the UDI metric to be applied and their implication is presented below [36].

- UDI100-500: the range for considered effective with daylight alone or the supplementation of artificial lighting
- UDI500-2000: is either desirable or at least tolerable
- UDI>2000: is said to cause visual and/or thermal discomfort

The UDI metric is basically the frequency of the occurrence of the defined illuminance (lux) ranges (100-500, 500-2000, >2000) on an hourly basis to the whole day-lighting year in a working space. However, the two points in the room which is set to be the reference should be considered mutually. Refer to Figure 4.3.

Considering the range of 500-2000 lux, instance 1 describes how the occurrence of such range in the working space is considered, the two points should be mutually in range of the 500-2000 lux. However, instance 2 describes when not to consider that the working space is in the said range – if there is a point that does not belong in the defined range.

Again, because there are only 5 WWR values being simulated, spline interpolation is again to be performed. The percent of occurrence in one whole daylighting year for every defined range that corresponds to varying WWR and orientation is then to be presented. See Figure 4.4 from a study from [34].

The acceptable percentages are not yet defined globally for this metric but as a rule of thumb, "acceptable" ranges are higher for UDI500-2000 (e.g. 50%) since this will mean that the working space is exploited with daylight while not being in the "harmful" state. On the other hand, UDI<2000 should be lesser since this will mean that the working space will be experiencing visual and/or thermal discomfort for occupants – 10-20% is "acceptable" and the lower is the more ideal [34].

4.2.2.2.1 Useful Daylight Illuminance (UDI) and its Capability

One of the most used daylighting metric is a fifty year old metric which is Daylight Factor (DF). DF is the ratio of the indoor illuminance due to daylight in a particular point of a working space to the outdoor horizontal illuminance under an unobstructed overcast sky [36]. It is a very common metric for daylighting assessment because of its simplicity and is still used in the present [38]. However, because it does not capture the scenario during non-overcast skies, this metric is said to be "unrealistic" [36].

Another common daylighting metric is the Daylight Autonomy (DA) metric. There are some studies that uses this metric [1234] [6] in optimizing window parameters. DA is just like a histogram of the number of occurrence (hourly or sub hourly) of a certain illuminance value (e.g. 500 lux) annually [36]. Unlike the DF metric, it utilizes the annual illuminance data thus the overcast and non – overcast skies are now being captured. However, the limitation of this metric is that the assessment of daylight is made independently point by point. For example, two different points aligned along the centre of the window in an office room are to be studied, one point is nearer the window and the other is farther. DA will give you for example that point "near" experienced 2000/4380 daylighting hours of 500 lux and point "farther" experienced 2000/4380 daylighting hours of 500 lux which is for example the desired illuminance. From the example scenario, it is good that the two points in the office experienced the desired illuminance (500 lux) almost 50% of the daylighting hours. However there is a huge possibility that for that one whole year, was an instance that point "near" experienced a higher illuminance while point "farther" experienced the desired illuminance. This will make visual discomfort in point "near" while maintaining the right amount of daylight for point "farther".

The mentioned limitations of DF and DA are the gaps that Nabil and Mardaljevic [36] addressed resulting in the creation of the metric UDI (Useful Daylight Illuminance). They first did a survey from the existing literature on what is the acceptable illuminance value that is most accepted by occupants. They concluded that "useful daylight illuminance" is within 100-2000 lux.

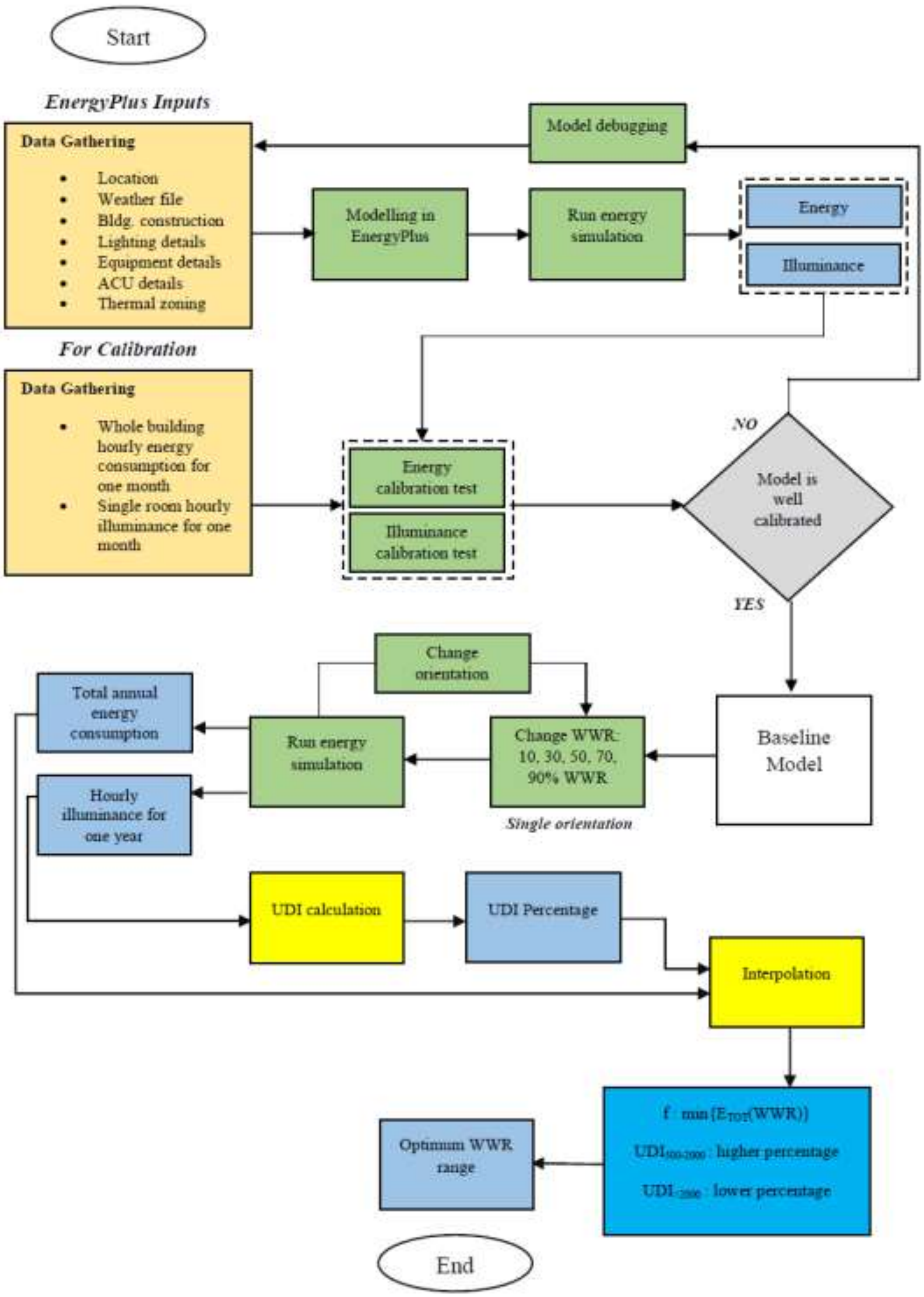
- 100 – 500 lux being the range for considered effective with daylight alone or the supplementation of artificial lighting
- 500 – 2000 lux is either desirable or at least tolerable
- > 2000 lux is said to cause visual and/or thermal discomfort

Mutual consideration of different points in a working space should be done in this metric to conclude for the entirety of the working space. Should there be at least one of the points being studied that does not fall in the 100 - 2000 lux range, it would mean that the working space in general is not experiencing the “useful daylight illuminance”. Also, it utilizes annual illuminance data to account for different sky conditions. With these, the authors were able to address the limitations of the previous metrics presented

4.2.2.3 Optimum Window to Wall Ratio

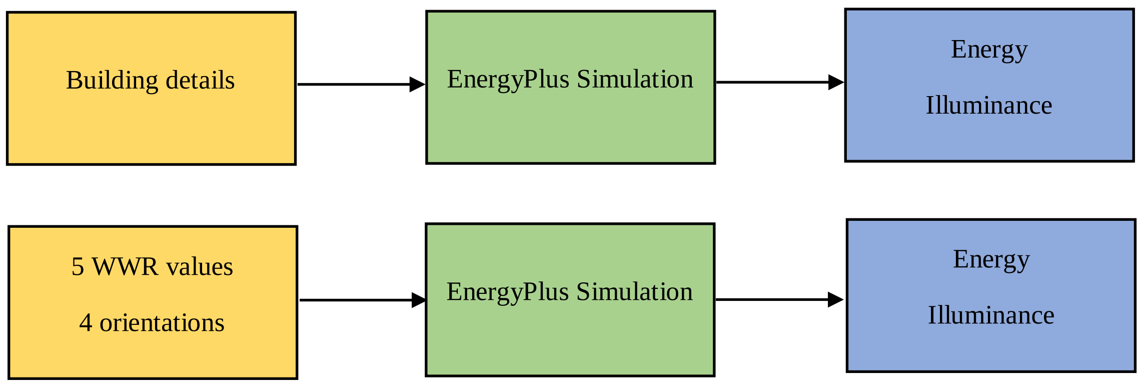
The WWR range that corresponds to min{ET(WWR)} and passes the day-lighting criteria being set for the Useful Daylight Illuminance will be deemed optimum.

4.3. Procedure/Method Flow



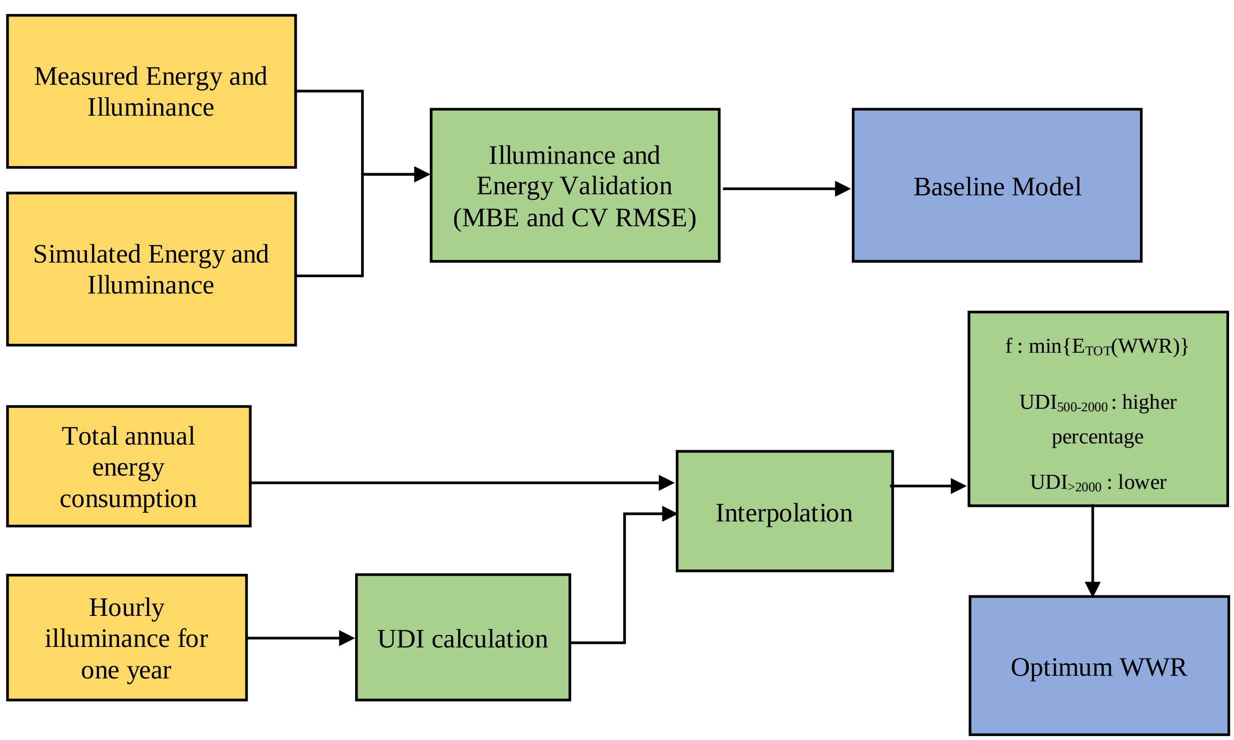
It starts with characterizing the inputs and parameters by gathering all the necessary building data to be used in creating the building energy model in EnergyPlus. Next is to perform an EnergyPlus simulation and then compare the results to the actual measurements through two statistical indices (CV RMSE and MBE) and do iterative calibration process if the model will not pass the criteria being set for the statistical indices. If it will pass the criteria, the model is then considered the baseline model for the parametric analysis. The window to wall ratio (WWR) is then changed from 10-90% with an increment of 20% for every orientation and simulated for their total annual energy consumption and annual hourly illuminance. There would be five simulations per orientation and their corresponding annual energy consumption and UDI is to be presented. The five discrete energy consumption and UDI as functions of WWR will undergo interpolation to make the results continuous. The WWR that will give the least energy consumption and will pass the criteria being set for UDI, will be deemed optimum. The process is then repeated for the remaining orientations.

4.4. Experimental Design



The first simulation is during the establishing of the baseline building energy model. The raw data in the form of energy (kWh) and illuminance (lux) is obtained through simulation in EnergyPlus using the building details as the input. The raw data produced will be used for calibration and validation. The second simulation is during the parametric analysis, 5 WWR values is simulated to be able to produce raw data in the form of energy (kWh) and illuminance (lux). These are repeated for 4 orientations. The energy and illuminance data will be used next to analyse the WWR values that will give the least energy consumption and to solve the UDI and be able to assess the daylighting performance of the various WWR values.

4.5. Information Flow



The first data processing is during the validation of baseline model. The raw data obtained from data-gathering which is the measured energy and illuminance and the simulated energy and illuminance are compared using statistical indices MBE and CV RMSE. The second series of data processing is during the parametric analysis. The raw data in the form of total annual energy consumption is interpolated. On the other hand, the raw illuminance data will be used to compute the UDI and interpolation is to be performed again. The continuous energy (kWh) and UDI as functions of WWR are then analysed and the WWR that corresponds to each of the following: minimum total energy consumption, higher UDI500-2000, and lower UDI>2000 will be deemed optimum.

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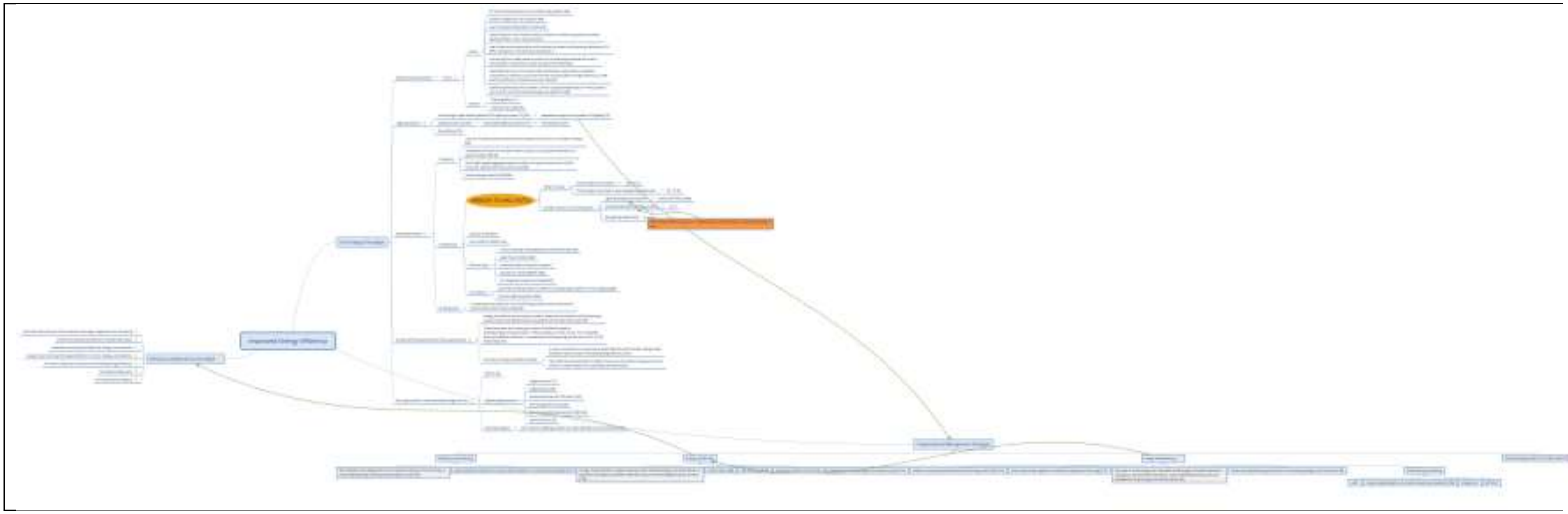
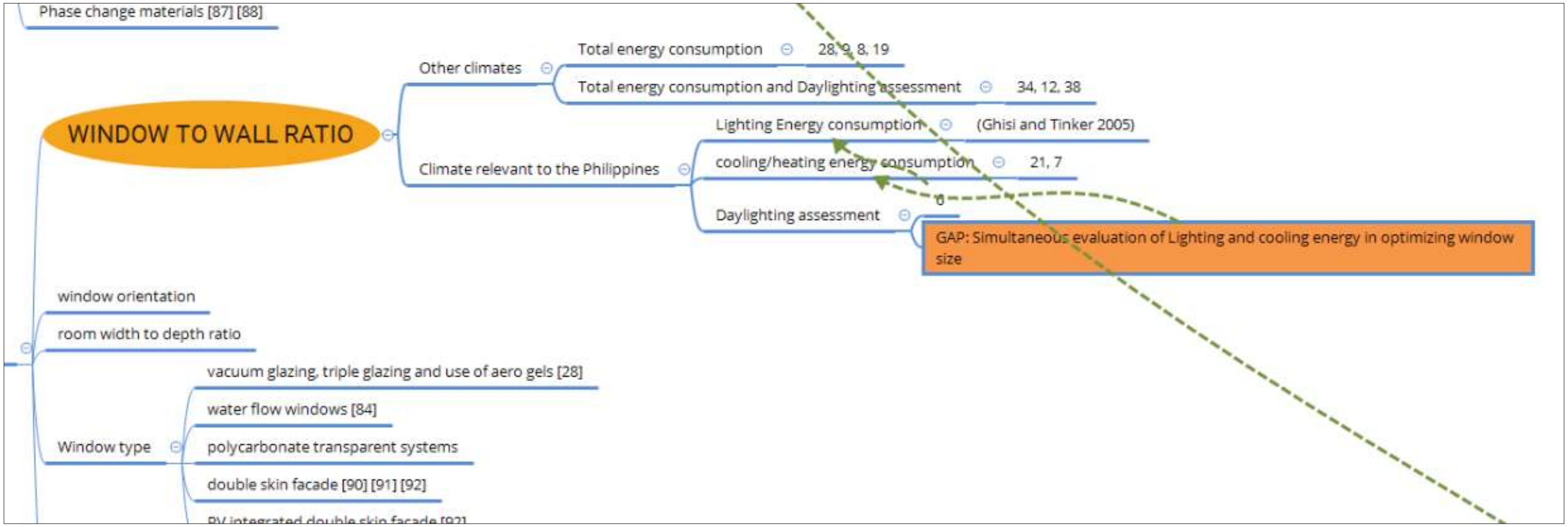
697 # 6. Appendix

698 ## *6.1. Literature Map*

699



700 **Figure 6.** Literture/concept map on Improved Energy Efficiency of Buildings

701 

702 **Figure 7** Literature/Concept map on WWR optimization

6.2. Figures

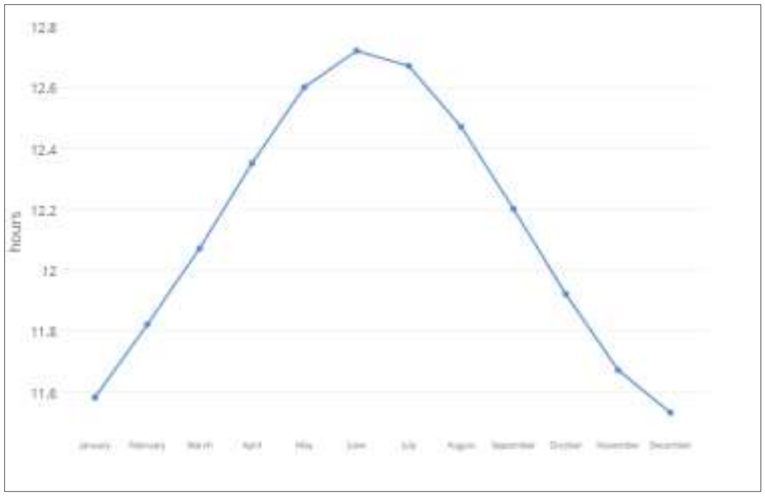


Figure 1.1 Monthly Daylighting hours data of Cebu, Philippines [39]

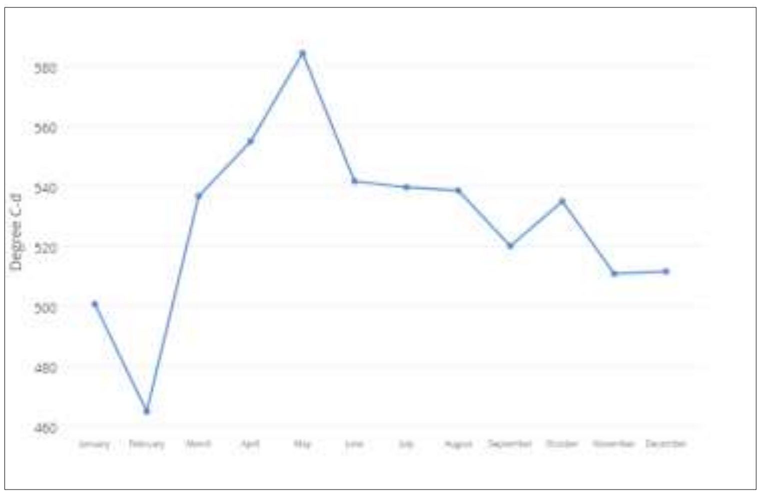


Figure 1.2 Annyal Cooling degree days of Cebu, Philippines [39]

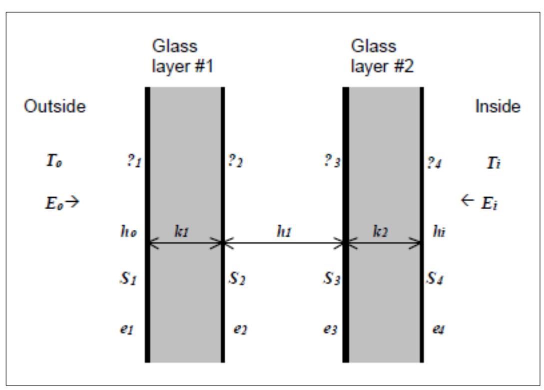


Figure 4.1 Double Glazed Window [48]

Here

E_o, E_i	=	Incident exterior and interior long-wave radiation (W/m^2)
h_o, h_i	=	Outside and inside air film convective conductance (W/m^2-K)
S_i	=	Radiation (short-wave and long-wave) from zone lights absorbed on face i (W/m^2)
T_o, T_i	=	Outside and inside air temperature (K)
ε_i	=	Long-wave emissivity of face i
h_j	=	Conductance of gas in gap j (W/m^2-K)
σ	=	Stefan-Boltzmann constant

$$E_o\varepsilon_1 - \varepsilon_1\sigma\theta_1^4 + k_1(\theta_2-\theta_1) + h_o(T_o-\theta_1) + S_1 = 0 \tag{1}$$

$$k_1(\theta_1-\theta_2) + h_1(\theta_3-\theta_2) + \sigma\frac{\varepsilon_2\varepsilon_3}{1-(1-\varepsilon_2)(1-\varepsilon_3)}\left(\theta_3^4-\theta_2^4\right) + S_2 = 0 \tag{2}$$

$$h_1(\theta_2-\theta_3) + k_2(\theta_4-\theta_3) + \sigma\frac{\varepsilon_2\varepsilon_3}{1-(1-\varepsilon_2)(1-\varepsilon_3)}\left(\theta_2^4-\theta_3^4\right) + S_3 = 0 \tag{3}$$

$$E_i\varepsilon_4 - \varepsilon_4\sigma\theta_4^4 + k_2(\theta_3-\theta_4) + h_i(T_i-\theta_4) + S_4 = 0 \tag{4}$$

Figure 4.2 Heat balance Equations for Double glazed Windows [48]

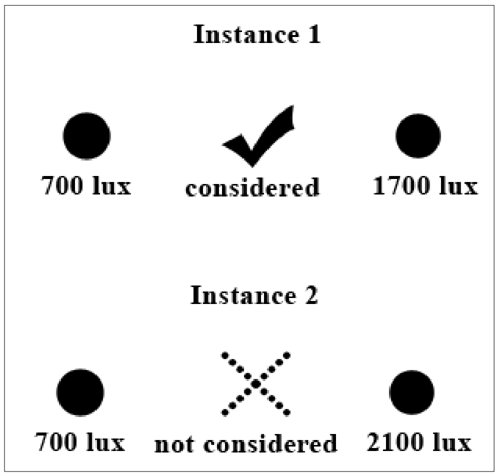


Figure 4.3 UDI concept

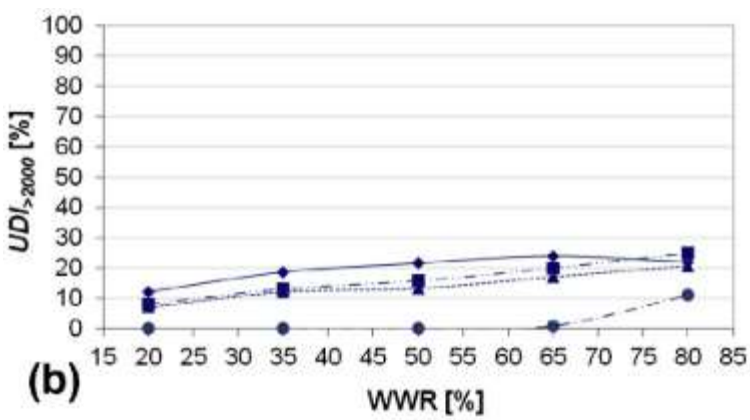


Figure 4.4Screenshot of UDI>2000 result from Francesco Goia [34]

6.3. Tables

Table 4.1 Building Constrcution Data

Material	Thickness (Meter)	Conductivity (W/m-K)	Density (Kg/m3)	Specific Heat (J/kg-K)
Walls				
Layer 1				
Layer 2				
Roof				
Layer 1				
Layer 2				
Floor				
Layer 1				

Table 4.2 Window Properties

Window Material	U – factor	Solar Heat Gain Coefficient	Visible Light Transmittance
Layer 1			
Layer 2			

Table 4.3 Lighting, Equpment, and ACU data

Room	Description	Size	Schedule
SAFAD Rm. 1	People	Persons	
	Artificial Lighting	Watts	
	Equipment	Watts	
	ACU	Specifications Set-point	

Table 4.4 Acceptance criteria for BEM

Guideline	Monthly		Hourly	
	MBE	CVRMSE	MBE	CVRMSE
ASHRAE guideline 14	5	15	10	30
IPMVP	20	-	5	20
FEMP	5	15	10	30